Malaysian Journal of Civil Engineering 20(1) : 89 - 106 (2008)

PERFORMANCE OF CS-SLEEVE UNDER DIRECT TENSILE LOAD: PART I: FAILURE MODES

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Abstract: Tensile resistance of a sleeve connector used to connect between two structural components by confining grouted reinforcement bars relies on the bond interaction among reinforcement bars, sleeve and grout. Slippage of the reinforcement bars is customary cause of damage in end-to-end grout-filled reinforcement connector under direct tensile force. In this study, a total of nine specimens with different configuration, in terms of sleeve lengths, sizes, configurations, rebar surface conditions and grouting material, were subjected to tensile test. This paper presents the result obtained from tests conducted on the proposed CS-Series specimens and discusses the failure mode as well as the mechanisms that governed the tensile resistance of the specimens. The test data indicates that threads on reinforcement bar had significantly deteriorated the bonding mechanism between reinforcement bars and grout. None of the specimens could achieve the required strength. However, the understandings of the causes of failures obtained from the study provided essential basis for future research.

Keywords: *splice sleeve; grout; end-to-end connector; bond; precast concrete*

1.0 Introduction

Ever since Dr. Alfred A. Yee, one of the pioneers, introduced grout-filled splice sleeve technique (MNB Sleeve) to the world, it had been a popular preference in the construction industry, initially in Japan, then worldwide. In 1981, sleeve technique was widely used in 5-story residential projects under Housing and Urban Development Board (HUD) of Japan. Soon after in 1990s, its applications in high-rise building over 30 stories were very common. These includes 30-story residence tower, Shin Kawasaki, 37-story

Ohkawabata high-rise residence (1989), 30-story Las Vegas MGM Grand Hotel (1991), 39-story Paramount tower in San Francisco (1999), and 56-story Shiodome H residential tower in Tokyo (2002). NMB sleeve has astonishing records throughout the history of as it went through several events of severe earthquakes without enduring much defects and had save lives of many people, particularly earthquakes in Island of Cuam (1994) and Kobe, Japan (1995) with the magnitude of shaking of 8.2 and 7.9 Richter Scale (RS) accordingly.

The constraint of raw materials and continuous consumption of steel metal had led to continuous increase in price of steel. Construction industry desperately demands for more economical solution as alternatives for conventional conservative codes of practice. Conventional reinforcement bar lapping system requires great amount of steel. Recognizing the capabilities and advantages of a sleeve system, it may be the solution for the raw material crisis. Therefore, the studies are conducted to innovate and develop new type of sleeve connector.

A sleeve is a cylindrical shape mechanical steel coupler that is utilized to splice reinforcement bars. It is a type of the end-to-end rebars connector, which utilizes non-shrink high strength grout as load transferring medium and bonding material. Reinforcing bars are inserted into it from the both ends to meet at the center before grout is filled. Application of sleeve in precast concrete structures as connection system can accelerate the speed of erection, significantly reduces required rebar lap length, and guarantees higher quality assurance.

The configurations of a sleeve should be design properly in order to ensure maximum structural performance. It confines the grout that bonds the end-to-end arranged reinforcement bars in order to enhance the bonding performance. It enhances bonding property to grab on reinforcement bars firmly, and takes part in sustaining tensile load itself to ensure continuities of reinforcement bars; therefore, the adequacy of a sleeve is governed by (1) the bonding properties of grout, (2) sleeve tensile resistance. Ideally, a sleeve should offer bonding and tensile resisting capacities that are comparable to the tensile resistance of reinforcement bar in order to ensure optimum usage of rebar capacity. In fact, it should outperform a reinforcement bar to provide safety factors to tolerate with unpredictable deterioration variables such as quality of work.

In this preliminary study, a type of sleeve was proposed and tested in the laboratory to study governing factors that contribute in structural performance of a sleeve. The failure modes of the proposed specimens were investigated to understand their failure mechanisms

2.0 Application of a splice sleeve connector

A splice sleeve connector can be utilized in both precast concrete structure as well as conventional concrete system, especially when lapping of reinforcement bars is required. In precast concrete structure, sleeve can be used for connection system for skeletal frame systems, such as beam-to-column, beam-to-beam connection, column-to-column connections and others. Meanwhile, for reinforced concrete structures, it acts as an alternative lapping system that ensures continuities of reinforcement bars.

However, the ultimate goal of the research focuses on developing a suitable splice sleeve connection system for precast wall panel structures. Figure 1 shows the application of proposed sleeve in precast wall panels system. It is used as joints for wall panels and to ensure continuities among them in order to form a load-bearing structural system.

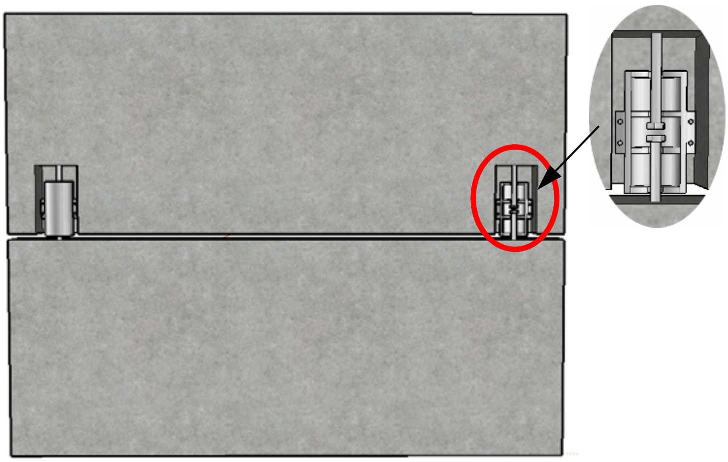


Figure 1: The proposed application of the CS-Sleeve for precast concrete load-bearing panel system

In precast load-bearing wall system, the precast wall will sustain the axial load, while the connection system will have to take the horizontal shear load (Figure 2a) and flexural tensile force (Figure 2b). In this feasibility study, the integration of loads was simplified into tensile force only in order to save time and cost. Therefore, simple tensile pulling test was conducted to study the proposed sleeve system.

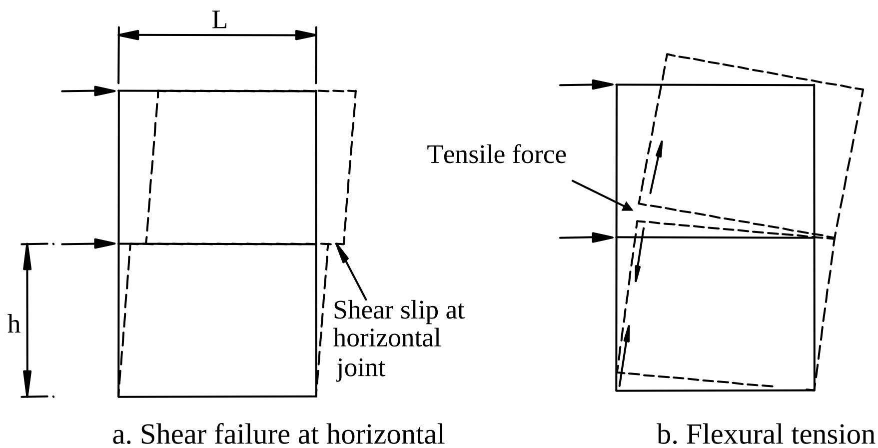


Figure 2: Types of loading for precast panel system

3.0 Experimental Setup

A total of ten specimens, including a control specimen, were prepared for tensile test in the laboratory. A Y16 reinforcement bar acted as control specimen to evaluate the performance of the nine proposed sleeves. The specimens were varied in terms of sleeve dimensions, lengths, sizes, configurations; rebar conditions, and bonding materials (Figure 3), in order to study and to compare the effects of these parameters.

The mild steel sleeves were manufactured in factory before being grouted in laboratory. Figure 4 illustrates typical design of the proposed sleeve. Steel plates were welded in the sleeve to prevent nut ended reinforcement bars from being pulled out of the sleeve. The semi circular sleeves were hold together by the bolts and nuts that grabbed on the steel plates that attached to the edge of the sleeves. Figure 5 presents the casting of the specimens with non-shrink, high strength grout in the laboratory.

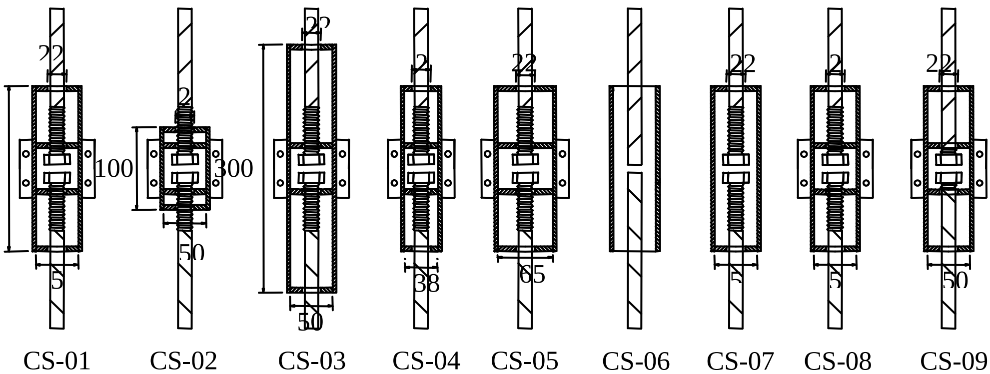


Figure 3: Proposed specimens for tensile test

Figure 4: Preparation of specimens

Figure 5: Casting of specimens

Figure 6: Installation of strain gauges on the reinforcement bar

Figure 7: Installation of strain gauge on the steel sleeve

In order to acquire the strain condition of reinforcement bars during testing, electric resistance strain gauges were installed onto the surfaces of reinforcement bars. The surfaces of reinforcement bars were grinded cautiously to procure smooth surfaces at about the size of strain gauge, so that strain gauge can attach on it firmly. The strain gauges were then covered by polyester (Figure 6) before it was tapped with a vinyl/mastic tape for insulating and moisture sealing. Besides that, strain gauges were installed on the mild steel sleeve (Figure 7) to monitor responds of the sleeve under loading.

Figure 8 demonstrates the setup of the hydraulic actuator for direct tensile test. Specimens were placed vertically on the platform while the actuator grabbed on the reinforcement bars at both ends at the pressure of 11 MPa. Then, as the testing process launched, the arm of the hydraulic actuator moved upward, causing mighty pulling force onto reinforcement bars at opposite directions. The rate of pulling force was 0.2kN/s throughout the testing. The data obtained from the testing consisted of load (kN), displacement (mm), steel strain ($x10^{-6}$) and also sleeve strain ($x10^{-6}$). The variation of load is plotted against displacements and strain readings for analysis.

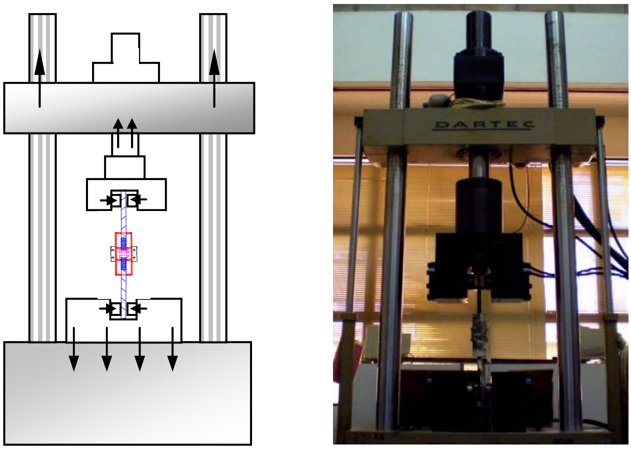
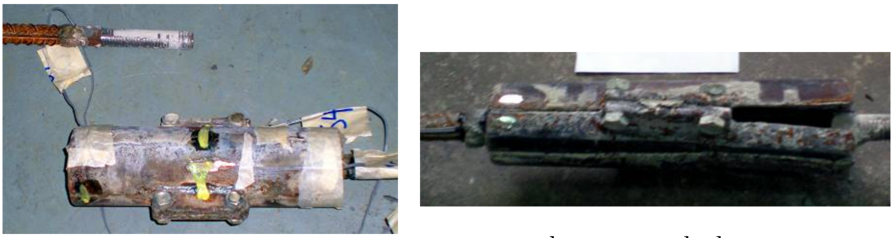


Figure 8: Tensile test were conducted in laboratory

4.0 Result and Analysis

Table 1 summarizes the performance of the proposed CS-Series specimens. It lists out the results obtained through tensile tests, which include ultimate tensile capacities, corresponding displacements and failure modes of the specimens. It shows that the loading capacities of the specimens ranged from 40.922kN to 101.795kN. The maximum loading capacity that the specimens could offer was 101.795k. However, based on the control specimen, a Y16 reinforcement bar yielded at 114.5kN and reached ultimate capacity at 133kN. Obviously, the performance of the specimens was unsatisfactory as the best achievement that the CS-Series could provide was only 76.5% of the required strength.

All of the proposed specimens, except CS-06, ended up with dislocation of reinforcement bar, where by they slipped out of the sleeve due to excessive tensile forced. Some specimens had their nuts remained inside the sleeve (Figure 9a) while others had their nuts firmly clamped on the reinforcement bars when the grout crushed (Figure 9b). Basically, there are four major modes of failure; (1) the nut skid off from the rebar, (2) slippage and pullout of reinforcement bar, (3) crushing of grout, (4) pullout of the grout from the sleeve.



a. nut pulled out

b. grout crushed

Figure 9: Failure modes of sleeves under tensile test

Table 1: Summary of performance of all Specimens

Specimen	Description	Ultimate Load, P (kN)	%	Stroke (mm)	Failure mode
CS-Bar	1Y16	133kN		-	-
CS-01	ID = 50 mm, *H = 200 mm,* T = 4.5 mm, TL = 70 mm	86.956	65.4	8.720	Nut pulled out thread sheared off Bond slipped
CS-02	ID = 50 mm, *H = 100 mm,* T = 4.5 mm, TL = 70 mm	98.419	74.0	26.301	Nut pulled out Thread sheared off Bond slipped Grout crushed
CS-03	ID = 50 mm, *H = 300 mm,* T = 4.5 mm, TL = 70 mm	80.049	60.2	4.541	Nut pulled out Thread sheared off Bond slipped
CS-04	*ID = 40 mm,* H = 200 mm, *T = 4.05 mm,* TL = 70 mm	85.272	64.1	17.094	Grout crushed Sleeve end split
CS-05	*ID = 65 mm,* H = 200 mm, T = 4.5 mm, TL = 70 mm	84.305	63.4	6.823	Bond slipped

Table 1 (cont.)

CS-06		40.922	30.8	0.995	Grout broke apart and being pulled out
	Cylinder ID = 50 mm, H = 200 mm, T = 4.5 mm				
CS-07	Sleeve without inner segments	72.516	54.5	7.038	Grout crushed Sleeve end split
	ID = 50 mm, H = 200 mm, T = 4.5 mm, TL = 70 mm				
CS-08	Mortar ID = 50 mm, H = 200 mm, T = 4.5 mm, TL = 70 mm	70.549	53.0	6.736	Nut pulled out Thread sheared off Bond slipped
CS-09	ID = 50 mm, H = 200 mm, T = 4.5 mm, TL = 20 mm	101.795	76.5	5.555	Nut pulled out Thread sheared off Bond slipped

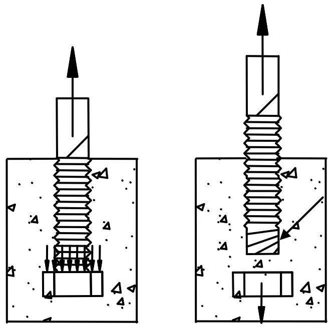
*Note: ID = internal diameter of sleeve, H = Sleeve height, T = Sleeve thickness, TL = Thread length of reinforcement bars

4.1 Failure modes and mechanism of failure

4.1.1 Nuts being pulled off from the reinforcement bar

Specimens CS-01, CS-02, CS-05 and CS-08 showed similarities in their failure modes; (1) the threads on the reinforcement bars and nuts sheared off, (2) bond slip between rebar and grout. Their reinforcement bars had approximately 70mm of thread length. A nut was screwed onto each of the reinforcement bar. It significantly increased effective bearing areas of the reinforcement bar to resist slippage.

As incremental force was applied onto the reinforcement bar, the nut tended to move along with the reinforcement bar towards the direction of the force. However, it was resisted but the grout surrounding it. This generated a distributed stress onto the bearing areas of the nut (Figure 10a). The nut relied on the shear resistance of the threads to clamp onto reinforcement bar. Unfortunately, it was not strong enough. The orientation of thread was shallow in depth and closely aligned together. This led to higher high bearing area but limited shear area (bearing/shear ratio), causing insufficient shear resistance of the threads. Therefore, as pulling force reached the shear capacity of the threads toward slippage, it sheared off (Figure 11). By then, the nut was unable to clamp onto the reinforcement bar (Figure 10b) and eventually, the reinforcement bar slipped out of the sleeve, leaving nut remained inside it (Figure 12).



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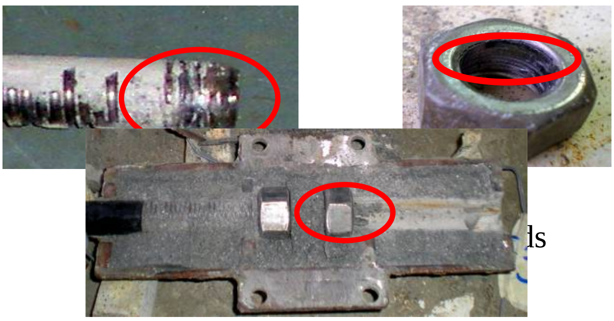
(a) (b)

Figure 10: Mechanism of nut being pulled off from reinforcement bar



ls

Figure 12: Nut remained inside the sleeve as specimen CS-01 failed

4.1.2 Slippage and pullout of reinforcement bars

All the specimens except CS-06 presented slippage of reinforcement bars as the major cause of failure. The reinforcement bars of the specimens slipped, leaving behind dusty smooth surface of grout. It was resulted due to crushing of grout key and slipping of reinforcement bar from the grout (Figure 13).

Figure13: Dusty, smooth surface of gout due to bar slippage of specimen CS-09

Specimens CS-01 and CS-09 were identical in all aspects except for the surface conditions of their reinforcement bars. Threaded reinforcement bars were used in CS-01 while the reinforcement bar used for CS-09 remained as its ordinary condition (Figure 14). Specimen CS-09 could sustain up to 101.795kN while specimen CS-01 could only sustain up to 86.956kN. It was observed that reinforcement bars in CS-09 was at the advantages of (1) larger effective cross sectional area, (2) ribs pattern that enhance the mechanical interlocking properties of the specimen.

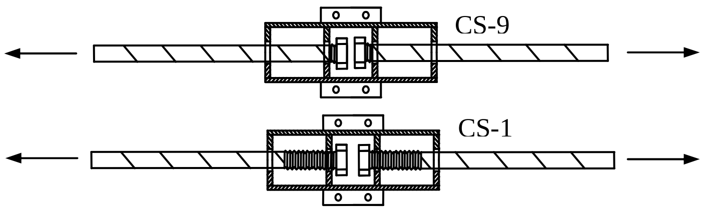


Fig. 14: The threaded length of reinforcement bars in CS-1 and CS-9

In order to thread a rebar, its surface had to be carved for approximately 1-2 mm in depth. This had caused scratches and damages on reinforcement bar as well as reduced the effective cross sectional area in resisting tensile force that significantly influenced the tensile capacity on reinforcement bar. However, the effect of the reduction of cross sectional area was insignificant in this situation due to poor bonding mechanism that had already failed before reinforcement bar yielded.

Through the comparison among the specimens, where obviously specimen CS-09 out performed other specimens, it was noticed that the existence of thread had affected the bonding mechanism between reinforcement bar and grout. This observation was supported by the bonding mechanism proposed by *Lurt and Gergely (1967).* The bond between conventional reinforcement bar and concrete rely on (1) chemical adhesion, (2) friction between rebar and concrete and (3) mechanical interlocking of bar ribs with the surrounding concrete. However, the effects of the chemical adhesion and friction are relatively insignificant, the mechanical interlocking become essential. In fact the rib pattern on the surface of reinforcement bar is purposely design for the mechanical interlocking aspect. In common practice, the height and spacing between ribs on rebars are designed to have relative rib area (the bearing/shear area ratio) about 0.1 in order to acquire the optimum bonding performance (Figure 15).

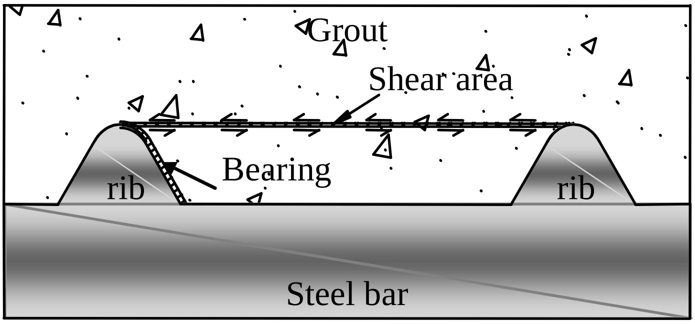


Figure 15: Bearing area of ribs and shear area of grout keys between ribs that is considered in bearing/shear area ratio

The threads on the rebar had altered the bonding mechanism, particularly in the aspect of mechanical interlocking. As pulling force was applied on reinforcement bars, the grout keys between the threads tended to resist the displacement of reinforcement bar. The stress was distributed and resisted by the threads and grout keys along the reinforcement bar (Figure 16a). The threads orientation had significantly increased the bearing areas but at the mean time decreased the shear areas of grout keys between the threads. This led to limited shear resistance and poor bonding mechanism. The effect of the mechanical interlocking ended when the grout keys failed in shear. This caused crushing and shear failure of the grout keys of which eventually caused reinforcement to slip (Figure 16b).

The proper design of rib patterns was essential in bonding mechanism. As pulling force was applied on reinforcement bar, the interlocks between grout keys and bar ribs resisted the slippage of reinforcement bar. The inclined surfaces of ribs caused a resultant resistance force perpendicular to them. This resultant force could be derived into two components; (1) normal and (2) longitudinal to the reinforcement bar (Figure 17a). Shear resistance of grout keys between bar ribs resisted the longitudinal component and therefore, slippage of reinforcement bar was controlled. Meanwhile, the normal components caused the grout to move away from reinforcement bar. This led to splitting force, which caused the grout to move outward and split at all direction. The combination of these two components caused the grout key slid upward along the ribs (Figure 17b) and eventually caused splitting cracks onto the grout surrounding reinforcement bar (Figure 18).

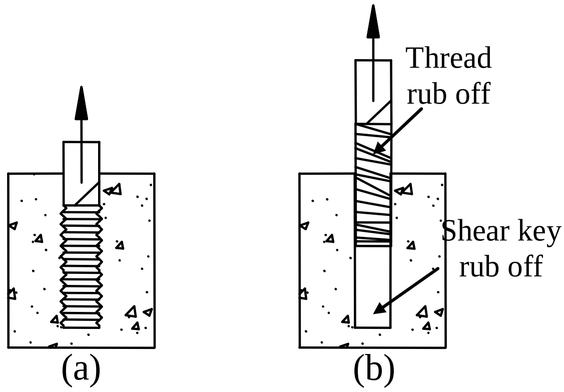


Fig. 16: Mechanism of slipped out of sleeve

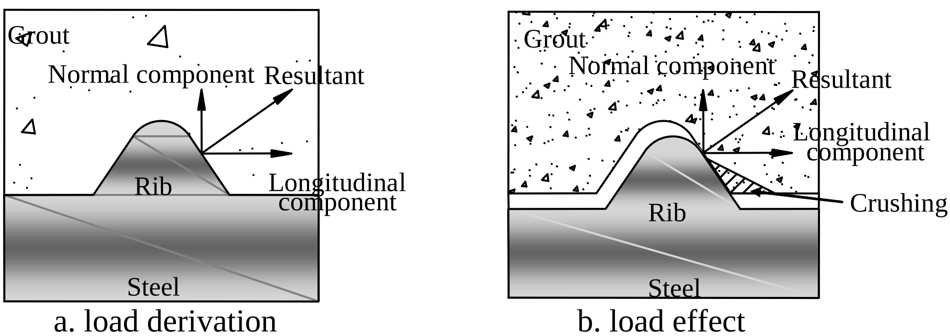


Figure 17: The resultant force acting perpendicular with the rib surface

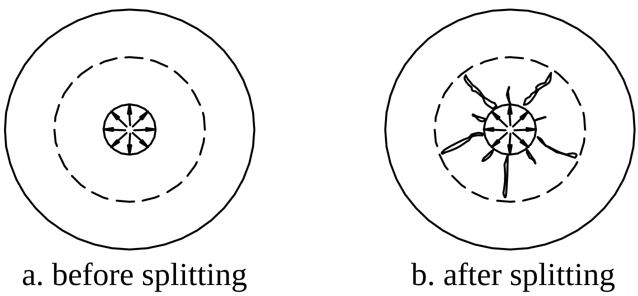


Figure 18: Splitting cracks of unconfined grout caused by normal component of resultant force

The effective shear resisting area was usually generated at the level of highest tip of the ribs. As the grout keys moved upward along the bar ribs, the effective shear resisting area of grout keys would reduce (Figure19). This would significantly decrease the slippage resistance of the reinforcement bar. Therefore, sleeve that enveloped the grouted reinforcement bar, resisted control the split of the grout. The splitting and expansion mechanism of the grout caused expending of sleeve as well and this had triggered tensile resistance of sleeve. The resistance force could be derived into tangent and perpendicular component. The perpendicular component caused the distributed force react towards at the center of grout, where reinforcement bar positioned. It controlled splitting cracks of the grout and kept the grout keys in position to ensure maximum available shear resisting area to control the decrease of shear capacity (Figure 20).

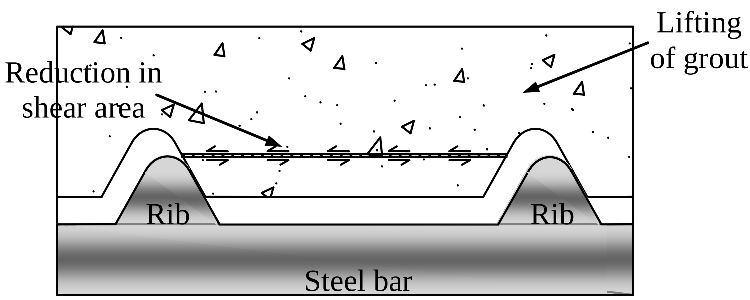


Figure 19: The effective shear area of grout keys reduced due to slight upward slide of grout caused by splitting

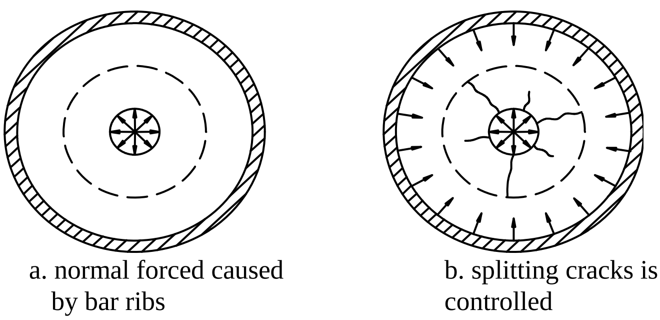


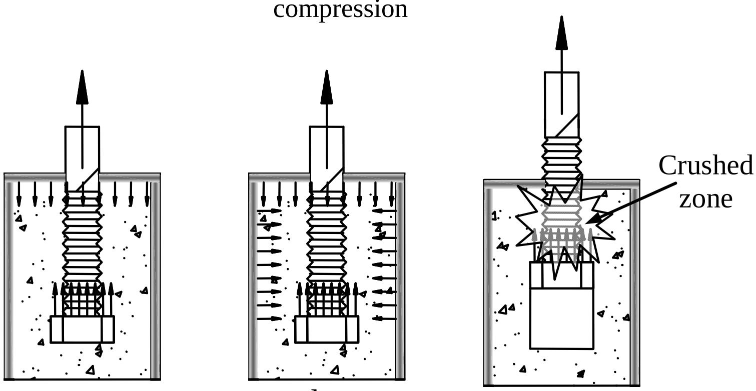
Figure 20: Confinement has controlled generation of splitting cracks

4.1.3 Crushing of grout

Specimens CS-02, CS-04 and CS-07 ended up with excessive compressive force that crushed a portion of grout. It was noticed that all of the specimens that underwent crushing had their nuts remain firmly on reinforcement bars (Figure 21). Figure 20 describes the crushing mechanism of grout under confined situation for specimen CS-07. The grout was surrounded by steel sleeve which act as restrain at all directions. As pulling force was applied on reinforcement bar, the nut that clamped on rebar tended to move upward together with reinforcement bar, forming distributed force heading the direction of source of pulling force. Then the steel sleeve that confined the grout will generate resisting force at the opposite direction (Figure 22a). This situation forced compressive force onto the grout, causing the grout to deform and expended laterally. However, the sleeve wall causing significant increase of compressive force (Figure 22b) then resisted the lateral expansion. As the compressive force exceeded the compressive strength of the grout, it crushed (Figure 22c).

a. CS-02 b. CS-04 c. CS-07

Figure 21: Crushing zones of the specimens CS-02, CS-04 and CS-05 due to excessive compression

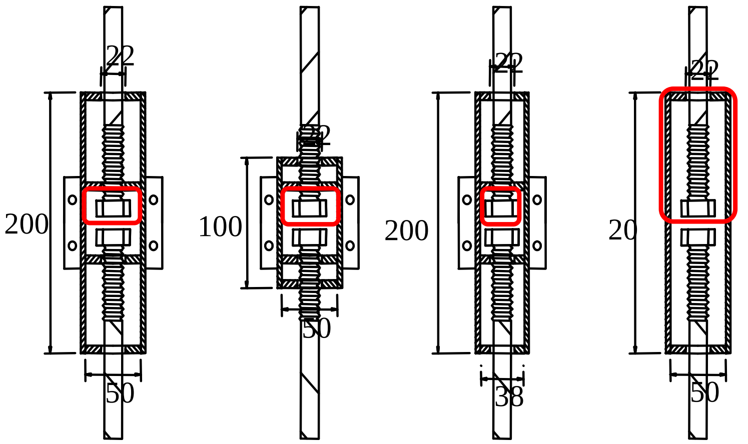


a. b. c.

Figure 22: Crushing mechanism of specimen CS-07

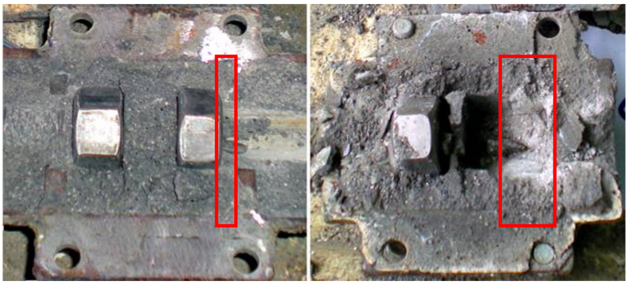
The results showed that the ultimate tensile capacity of the specimens was determined either by the compressive strength of the grout or the shear resistance of threads, of which had lower capacity. It seemed that the specimens with nuts being pulled out of rebar did not undergo crushing. Meanwhile, the specimens of which had nuts firmly attached to the rebar, suffer crushing failure under extreme tensile load.

It was noticed that the specimens with the compressive grout zone that have higher volume per effective area ratio (volume/area ratio) will have higher tendency of undergoing crushing (Figure 23). There was no middle restrain for specimen CS-07, leaving to larger volume of grout to sustain the compressive stress as compared to specimen CS-01, underwent crushing. Meanwhile, both specimens CS-04 and CS-01 had similar length of grout under direct compression. However, the effective area reduced due to reduction of diameter of sleeve. This also contributed to larger volume/area ratio as compared to specimen CS-01. Theoretically, if specimen CS-01 does not undergo crushing, neither do specimen CS-02. However, due to poor quality of workmanship, the location of nut for specimens CS-02 and CS-01 were not precisely placed at the specific intended locations. From Figure 24 that compares the location of nuts in the sleeves CS-01 and CS-02, it was obvious that CS-02 had larger volume/area ratio due to misallocation of nuts that was not precisely at the middle of the inner cellular grouting zone. This caused crushing of grout under high compressive forces of CS-02.



a. CS-01 Non-crushed | b. CS-02 Crushed | c. CS-04 Crushed | d. CS-07 Crushed

Figure 23: Detail of specimens CS-01, CS-02, CS-04 and CS-07

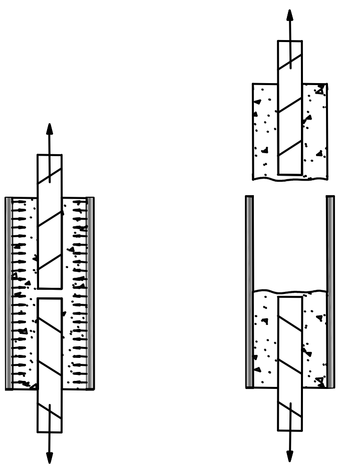


CS-01 CS-02

Figure 24: Comparison of volume/area ratio of specimens CS-01 and CS-02

4.1.4 Pullout of the grout from the sleeve

Specimen CS-06 comprised a steel cylinder without any capping at both end of the cylinder. It confined the grout at lateral direction only. As tensile load was applied, the stress was transferred along the rebar and to the grout through bonding mechanism. Due to strong mechanical interlocking bond between bar ribs and grout, the grout tended to move as a unit with rebar, toward the direction of pulling force. Unfortunately, the contact surface between the grout and the steel cylinder was smooth without provision of any ribs on it. This caused the top part and bottom part of grout tended to moved and slid at opposite directions. Due to the reason that grout is strong in compression but weak in tension, it split into two components and one of the grout slid out of the cylinder with the embedded rebar. Figure 25 and Figure 26 present the failure mode of specimen CS-06 and the surface of split of the grout.



a. b.

Figure 25: Split mechanism grout in steel cylinder

Figure 26: The grout split at the middle and slid out of the cylinder of specimen CS-06

5.0 Conclusion

A total of nine proposed specimens of CS-Series were tested under tensile loads. None of the specimens provided satisfactory performance of which the maximum loading resistance that they could offer was only 76.5% of the required loading capacity. Four types of failure modes were obtained. These includes nut being pulled out of the sleeve, slippage of bar, crushing of grout and grout slid out of the sleeve. The failure mechanism and causes of failure for each modes of failure were investigated. The understanding obtained through this study provides very important basis for future study of sleeve connectors.

Acknowledgement

The authors gratefully thank the CREAM (Construction Industry Research Institute of Malaysia) and CIDB (Construction Industry Development Board) for the financial support under research grant Vot. 73713.The experimental programs were conducted at the Structural and Material Laboratory of Faculty of Civil Engineering, University Technology Malaysia. The contribution of the technical staff is also acknowledged.

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